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R.M. YOUNG et al.: "Generation and behavior of fine particles in thermal plasmas-A review"

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Ullmanns Encyklopädie der technischen
Chemie, 4th edition, vol. 2, p. 400-404 (1972)

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Description

BACKGROUND OF THE INVENTION

5 This invention relates to a process and an apparatus for producing ultrafine particles of metals, metallic compounds and ceramics with high purity and controlled particle shape, particle size and particle size distribution by a plasma method in order to yield ceramic sintered bodies with highly controlled microstructures and constructions.

Ceramic ultrafine particles or powders are used for giving structural, functional or biotechnological ceramic materials (sintered bodies). With recent progress in studies, in order to meet requirements for fine ceramics partly used practically, for example, in order to obtain high physical properties such as high heat resistance, high strength, high toughness, etc., in the case of structural materials such as engine parts in cars, or in order to obtain uniformity in physical properties in the case of functional materials such as chemical sensors, there have been desired to have uniform grain sizes in ceramic sintered bodies in the range of about 0.5 to 5 μm , to have pores with a uniform size and distributed uniformly in ceramic configuration, or to have no pores depending on use, to have impurities in the crystal grain boundaries as small as possible, or to be controlled to have constant components.

Ceramic raw material powders can be produced by a grinding and classifying method, a wet method with chemical substances, or a gas phase method wherein fine particles are formed by synthesis by a dry method.

According to the grinding and classifying method, there are defects in that impurities are easily mixed, the resulting particles are angular and easily form large spaces irregularly when molded, it is difficult to classify raw material particles with uniform particle size in the range of 0.05 to 1.0 μm , which range is considered to be preferable in the present ceramic production technique to give crystal particles with most uniform in quality, and dense, small and uniform particle size, and particularly there is obtained a broad particle size distribution.

According to the wet method, in the case of oxide ceramics such as Al_2O_3 , SiO_2 , ZrO_2 , etc., there can be obtained spherical particles with the desired particle size directly, or primary particles having a very small particle size of 0.01 to 0.04 μm , said primary particles being able to give single particle size secondary particles with almost spherical in shape, and dense and desirable particle size by an improved treating method. In the non-oxide system, for example, Si_3N_4 can be obtained by an imide method wherein primary particles are as small as 0.05 μm or less. These fine primary particles grow by combining fine particles by a sintering treatment to large particles with uniform particle size depending on the sintering temperature and time. But it is inevitable to fuse the particles each other partly. Further, bridging easily takes place at the time of molding, which results in making it impossible to always produce products with high density.

According to the gas phase method, reaction gases previously mixed are introduced into a reaction zone, or reaction gases are directly mixed at the reaction zone. Since ceramic particles formed by synthesis or decomposition reaction have a melting point considerably higher than the temperature of the reaction zone, the growth of particles is difficult and the particle size obtained is about 0.01 μm , which size is about 1/10 of the desirable particle size of 0.05 to 1.0 μm . Although secondary particles may grow to some extent by collision of primary particles each other, it is difficult to control desirably the density, particle shape, particle size, and particle size distribution of the secondary particles. Thus, uniform dispersion of the particles at the time of molding is difficult, which results in failing to obtain dense molded products practically.

The gas phase method includes a plasma method, and particularly a hybrid plasma method, which are disclosed, for example, in Japanese Patent Unexamined Publication Nos. 55-32317 and 60-19034. According to these methods, one direct current (dc) arc plasma jet is combined with a high frequency induction plasma. The apparatus disclosed therein comprises a dc arc plasma torch and a high frequency induction coil, the central line of the both being owned jointly as shown in Fig. 5. According to these methods, there is a defect in that a starting material powder cannot be supplied to the high frequency induction plasma effectively.

The present inventors disclosed in Japanese Patent Unexamined Publication No. 60-77114 that spherical SiC having a particle size of 0.05 to 1.0 μm with almost single particle size was synthesized by a plasma method using a Si compound and a carbon compound as starting materials. More concretely, a Si compound such as SiH_4 is decomposed thermally at a temperature higher than the melting point of Si to form liquid particles, followed by reaction with a carbon compound such as CH_4 gas at a temperature higher than the melting point of Si to give spherical SiC powder having a particle size of 0.1 to 1.0 μm .

On the other hand, Japanese Patent Unexamined Publication No. 61-232269 discloses a process for producing B-containing SiC by introducing a carbon-free Si compound, or Si with a carbon-free boron compound or boron, yielding Si and B by reduction, pyrolysis or simple melting, making the temperature lower than the boiling point of Si but higher than the melting point of Si to form B-containing Si liquid spheres, followed by carbonization.

But according to these Japanese Patent Unexamined Publications, there is a problem in that the selection of starting materials is difficult. That is, when hydrogenated silicon such as SiH_4 gas is used as a silicon compound, the desired Si liquid sphere can easily be formed by pyrolysis, but the hydrogenated silicon is expensive at present. When a chloride such as SiCl_4 is used, Si or B can be obtained by reduction with hydrogen at a high temperature, but very corrosive HCl or Cl_2 is produced to deteriorate the apparatus, which results in raising a problem of maintenance of the apparatus. Further, when Si and B powders are used to directly form liquid spheres of (Si + B) by melting, it is difficult to obtain a high purity powder of submicron size, the surface of which is not oxidized, or even if obtained, particles are aggregated undesirably at the time of blowing to form large (Si + B) liquid spheres having a particle size of $1\text{ }\mu\text{m}$ or more. When vaporized and passed as Si and B vapors, such aggregation does not take place. But very high temperature and remarkable temperature uniformity are required to vaporize the whole blown Si and B, so that in practice, aggregated particles pass a low-temperature portion without vaporization, a considerably large amount of particles are collected as large particles. This is a problem.

In the case of materials other than Si series materials, for example, Al, Zr, Mo, etc., production of hydrogenated compounds and access to these materials are sometimes very difficult.

US-A-4 386 258 discloses a plasma reactor comprising an arc plasma torch, a quartz pipe, a high frequency induction coil, a reaction material introducing pipe and a plurality of gas discharging outlets. The arc plasma torch comprises a tungsten cathode, a copper anode serving also as a gas nozzle, and a plasma gas introducing inlet. In one example suitable for the introduction of reaction gas, the reaction material introducing pipe has a plurality of small holes through which the reaction material is jetted downwardly and inwardly. In another example suitable for the introduction of reaction material in the form of powder, the introducing pipe, shown as having a single central opening on the axis of the apparatus, opens in the vicinity of the arc plasma jet stream. In the reactor, an arc plasma and a high frequency plasma are generated, and the reaction material together with the arc plasma flows into the high frequency plasma flame.

US-A-3 989 512 discloses a heater assembly comprising cathodic plasma generating means for generating a column of plasma and a plurality of anodic plasma torches having their outlets symmetrically disposed about the axis of the column. A current is passed simultaneously between a generating means and each of the torches by way of the column and jets of plasma from the outlets which merge with the column. In a first example, three plasma torches are arranged in a horizontal plane about the axis of the heater assembly.

A pilot arc is maintained within each of these torches by means of separate electrical generators, and gas is fed through the torches so that a plasma jet emerges from the nozzle of each torch. The three jets of plasma are arranged to merge in the centre of the apparatus and provide a conducting region of confluence to which an arc may be struck from a cathode arranged vertically above the region of confluence. In a second example, three individual gas-shielded cathodes are provided, each of which produces a jet of plasma directed towards the anodic plasma zone. In operation, a stream of plasma leaves each of the individual cathodes as a high velocity jet and these streams merge at a point. It is stated that that point represents a low pressure zone into which powder feed stock may readily be fed, and such feed stock subsequently enters the principal arc column where required processing of the powder takes place.

Ullmanns Encyklopädie der technischen Chemie, 4th edition, vol. 2, pages 400 - 404 (1972) describes the construction and mode of operation of plasma torches. In particular, high-frequency inductive plasma torches are described although it is stated that the efficiency of torches which bring the working gas into a plasma state using induction heating is still very limited. It is explained that the high-frequency induction plasma is distinguished by a low gas flow speed and that the kinetic energy is therefore comparatively low so that the range of application is different from that of the arc plasma. It is stated the relatively large-volume highfrequency induction plasma of low flow rate appears particularly suitable for heating and melting powders in the plasma flame, provided that the particles have a suitable geometric form, that is, are pourable. The particle size must also, the Encyklopädie says, be within a suitable range (between 2 and $300\text{ }\mu\text{m}$). It is stated that in this manner refractory oxides can be re-melted in atmospheric or oxygen plasma to micro-spheres.

The Encyklopädie also includes a description of a triple plasma torch in which three electric plasma arc torches fed by direct current are arranged like the edges of a pyramid and the ionized gas flows meet at

the top of the pyramid. It is explained that if the voltage of a three-phase supply is applied across the anodes of the torch, a three-phase current circulates between the electrodes feeding the plasma additional electrical energy.

It is an object of the invention to provide a process and an apparatus for producing ultrafine particles of 0.05 to 1.0 μm particle diameter of metals, metallic compounds or ceramics by a plasma method.

The present invention provides a process for producing fine particles of a material in a plasma apparatus, which process comprises:

producing, using an anode surrounding a cathode, a direct current plasma current on a central axis of a work coil generating a high frequency induction plasma,

supplying the material as a starting material to the direct current plasma current from a top portion of the apparatus, and

passing the starting material through the centre portion of the high frequency plasma to heat and vaporize the starting material, and

recovering particles resulting from the vaporization, **characterized in that**, ultrafine particles having an average particle size of 0.05 to 1.0 μm of a metal, a metallic compound or a ceramic, are produced while recovering the whole amount of the starting material, a plurality of direct current plasma currents, each produced using a respective anode surrounding a respective cathode, are combined on the central axis of the work coil to produce a highly viscous direct current plasma flame, the direct current plasma and the high frequency plasma are connected to each other without separation between them, and the starting material is supplied, while excluding air, to the portion where the direct current plasma currents combine and is sealed by the highly viscous direct current plasma flame and moved, as it is, along the central axis to the high frequency plasma.

The invention also provides a hybrid plasma generating apparatus comprising means constituted by an anode surrounding a cathode for generating a direct current plasma current on the central axis of a work coil for generating a high frequency induction plasma and a hole provided on the central axis at a top portion of the apparatus for supplying a starting material, **characterized in that**, for producing ultrafine particles having an average particle size of 0.05 to 1.0 μm of a metal, a metallic compound or a ceramic, while recovering the whole amount of the starting material, a plurality of means, each constituted by a respective anode surrounded by a respective cathode, for generating direct current plasma currents are provided, said direct current plasma generating means are placed so that, in use, the direct current plasma and the high frequency plasma are connected to each other without separation between them, and so that the direct current plasma currents combine on the central axis of the work coil to produce a highly viscous direct current plasma flame, and the said hole is above the said direct current plasma generating means and so placed that starting material is sealed, in use, by the highly viscous direct current plasma flame and moved along the central axis as it is to the high frequency plasma.

Ways of carrying out the invention will now be described, by way of example only, with reference to the accompanying drawings, in which:

Fig. 1 is a schematic cross-sectional view of one example of the hybrid plasma generating apparatus according to this invention.

Fig. 2 is a schematic cross-sectional view of another example of the hybrid plasma generating apparatus according to this invention.

Fig. 3 is a schematic cross-sectional view of a direct current plasma generating apparatus.

Fig. 4 is a schematic cross-sectional view of a high frequency induction plasma generating apparatus.

Fig. 5 is a schematic cross-sectional view of a hybrid plasma generating apparatus comprising one direct current plasma generating means and one high frequency induction plasma generating means.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

The particle size of metals, metallic compounds or ceramics obtained in this invention is 0.05 to 1.0 μm in average.

When the particle size is smaller than 0.05 μm in the production of a sintered body from a metallic compound powder or ceramic powder, secondary particles are formed roughly, due to the action of surface charge of the particles or the action of liquid attached to the particle surfaces, and the green density is lowered at the time of molding to distribute large and small pores in uncontrolled state in the green body.

On the other hand, when the particle size is larger than 1.0 μm , it becomes difficult to densely sintered Si_3N_4 , SiC and the like substances which are usually difficult to be sintered.

Further, according to conventional plasma methods, even if the average particle size is in the range of 0.05 to 1.0 μm , when the particle size distribution is wide, rough secondary particles are easily formed, and

there is a tendency to grow abnormally to form undesirably large particles due to strong reactivity of fine particles at the time of sintering a green body. Such a problem is also solved by this invention.

According to the recent particle surface treating technique, or particle surface charge controlling technique in a powder-liquid system, or dispersing technique in protective colloid and the like, the particle size in the range of 0.05 to 1.0 μm with a very narrow single particle size distribution can provide a green body with uniform quality and high density, and a sintered body of remarkably dense with small and uniformly controlled grain sizes. When the particle shape is needle-like or angular, there is a tendency to roughly aggregate or to bridge so as to lose uniform quality of green body according to conventional plasma methods. Therefore, it is preferable to use spherical or cubic particles for molding and sintering. But, such a problem is solved by this invention.

This invention is characterized by charging the supplied starting material to a high-temperature gas flow effectively, leading the supplied starting material to the central portion of high frequency induction plasma effectively, and making the residence time of the supplied starting material at the high-temperature portion long. Since this invention makes it possible to melt and vaporize the whole supplied starting material uniformly, it becomes possible to select the starting material among metals, metallic compounds and ceramics depending on purposes and other conditions. Therefore, the problem of difficulty in selecting the starting material is solved. Further, it also becomes possible to produce various ultrafine particles of metals, metallic compounds and ceramics other than Si series ones.

Examples of the products obtained by this invention are ZrO_2 , TiO_2 , Al_2O_3 , MgO , CeO_2 , SnO , ZnO , SiO_2 , ZrB_2 , TiB_2 , NbB_2 , MoB , Mg_2Si , Y_5Si , TaB_2 , WB , VB_2 , CrB , HfB_2 , CeSi_2 , ThSi_2 , U_3Si_2 , MoSi_2 , VSi_2 , TaSi_2 , WSi_2 , TiSi_2 , ZrSi_2 , NbSi_2 , HfSi_2 , TaSi_2 , AlN , BN , TiN , Si_3N_4 , ZrN , VN , NbN , TaN , Cr_2N , HfN , TiC , B_4C , TaC , WC , Cr_3C_2 , ZrC , NbC , VC , MoC , HfC , TiS_2 , CrS , MnS , CoS_2 , TiAl , AlMo_3 , etc., alone or as a mixture thereof, and metals such as B, Si, Al, Ti, Cr, Mn, Fe, Co, Ni, Cu, Zn, Y, Zr, Mo, Sn, Ta, W, Hf, V, Nb, Pt, etc., alone or as a mixture thereof.

The starting material can be used in the form of either powder, liquid or gas, or in the shape of wire, rod-like material, or the like. Further, it is possible to use particles having a slightly wide particle size distribution.

This invention is illustrated more in detail referring to the drawings.

Fig. 1 is a schematic cross-sectional view of one example of the hybrid plasma generating apparatus according to this invention. In Fig. 1, a plurality of dc plasmas 1 and a high frequency induction plasma 2 are combined to form a hybrid plasma. A plurality of dc plasma guns 3 are positioned on the periphery of the top portion of the apparatus and a work coil 4 for high frequency plasma is positioned under the dc plasma guns so that the central axis of the periphery for positioning the dc plasma guns coincides with the central axis of the work coil 4. In this case, it is not always necessary to position the dc plasma guns on the periphery of the top portion. The important thing is to position the dc plasma guns so as to direct dc plasma currents toward the center of the high frequency induction plasma, and the dc plasma and high frequency plasma are connected without separation. More in detail, it is preferable to direct each dc plasma at an angle of 45° or less with regard to the central axis of the work coil 4. When the angle between the central axis and the dc plasma becomes smaller, there is a tendency to undesirably increase the speed of the dc plasma so as not to melt the starting material powder sufficiently particularly when the starting material powder has a higher melting point. In such a case, suitable conditions can be obtained by, for example, making the angle larger, raising the power higher, and the like.

A starting material supplying hole 5 is provided at the top portion of the apparatus above the dc plasma guns 3 and at the central axis of the work coil 4.

A starting material of metal, metallic compound or ceramic is charged from this supplying hole 5. A plurality of dc plasma flames are jetted from the dc plasma guns toward the center of the periphery on which the dc plasma guns are positioned, and are combined on their way to form a plasma flame or a high-temperature gas current toward the center of the high frequency plasma. Since the plurality of dc plasma guns are positioned at outer portion in the apparatus as shown in Fig. 1, the starting material supplied from the supplying hole 5 is inhaled by the plasma flame effectively at the central portion and jetted downward toward the center of the high frequency plasma. Since the combined dc plasma flames have a speed along the central axis of the high frequency induction plasma and the high-temperature gas current is highly viscous, the starting material inhaled in the combined flames is not scattered and passes through the central portion of the high frequency induction plasma to be melted or vaporized with heating.

In order to melt and vaporize a solid, there are known and used a method of irradiating with a laser, or ion or electron beams, a method of collecting heat rays radiated from a high-temperature substance such as a solar furnace, image furnace, infrared oven, etc. to one point and irradiating it, a method of using thermal plasma gas, or a method of using heat transfer/radiation from a heating medium or a furnace wall, and the

like.

Among these methods, the use of thermal plasma is preferred since the ultra-high temperature can be obtained in relatively large amount with ease and the control is easy, so that the thermal plasma is widely used for melting low-melting substances such as ceramics and high-melting substances and used in a melt cutter, a flame spray apparatus, and the like.

The present inventors have noticed the convenience and largeness of productivity of the thermal plasma, and tried to use the thermal plasma for melting and vaporizing metals, metallic compounds and ceramics. The structures of apparatus used therefor are shown in Figs. 3 to 5.

In the case of dc plasma alone as shown in Fig. 3, which is a so-called flame spray apparatus, melting is possible but vaporization of the whole starting material is difficult. In Fig. 3, numerals 1 and 3 are the same as explained in Fig. 1, numeral 8 denotes a plasma gas and numeral 9 denotes a starting material powder.

In the case of high frequency induction plasma alone as shown in Fig. 4, there are many defects in that complete vaporization of the starting material is difficult, the plasma is unstable and easily disappears when the starting material is added thereto, it is difficult to charge the whole supplied starting material powder into the central portion without dispersion outward, some of the powder adheres to the wall, and the like. In Fig. 4, numeral 2 denotes a high frequency induction plasma, numeral 4 denotes a work coil for high frequency induction plasma, and numeral 9 denotes a starting material powder.

In the case of a hybrid plasma consisting of one dc plasma and one high frequency induction plasma as shown in Fig. 5, when a starting material powder 9 is blown into a dc plasma 1, since entrance of the powder into the dc plasma is difficult due to high viscosity of the dc plasma (high-temperature gas current), the powder does not pass through a high frequency plasma flame but pass through an outer portion thereof to become non-vaporized molten body with a large particle size. Alternatively, when the powder is blown from an inlet 5, there is a fear of blocking off the inlet. Even if not blocked off, there are many disadvantages in that build up 10 of molten metal is formed around an outlet for the dc plasma 1 which results in making the operation unstable, some powder passes around the dc plasma and enters into a high frequency plasma 2, and large particles having a particle size of 10 to 100 μm seemed to be derived from non-vaporized powder are recovered. Further, when a part of the starting material powder enters into the center of dc plasma, it is instantly raised to the high temperature in a narrow cross-sectional area, so that the speed of the powder or molten metal sphere becomes too fast due to the remarkably fast gas flow rate, which results in making some of the powder pass through the high frequency plasma flame in a non-vaporized state.

To sum up, when the apparatus as shown in Fig. 5 is used, the starting material powder cannot be supplied to the high frequency plasma effectively. This seems to be caused by the high viscosity of the high temperature gas. That is, the high frequency plasma flame itself has a high viscosity and makes it difficult to take the starting material powder into the inner portion of the plasma flame. In order to solve this problem, there have been made many attempts to analyze the interior gas flows, to improve starting material introducing positions, to adjust the amounts of various gases to be introduced, for supplying the starting material to the interior of the high frequency plasma as effective as possible.

But the above-mentioned methods are insufficient to solve the problem. That is, when the kind of starting material, the introducing amount of starting material and the plasma power are changed, the interior flows are changed and proper starting material introducing positions and various introduced gas amounts are also changed. Consequently, it is impossible to carry out sufficient analysis considering various cases, and thus trial and error is to be employed.

In contrast, when a plurality of the dc plasma guns are positioned so as to combine the dc plasma currents as shown in Fig. 1 and the starting material is passed through the center of the combined dc plasma currents, the starting material is sealed by the highly viscous dc plasma flame to move along the central axis as it is and forced to be supplied to the high frequency plasma. According to the process of this invention, even if reaction conditions are changed slightly, the starting material is always supplied to the high frequency plasma efficiently. As a result, the whole amount of the starting material can be recovered as a product having a particle size of 0.05 to 1.0 μm , while the operation can be carried out stably for a long period of time.

According to the process of this invention, there can be obtained the following advantages.

(1) The starting material is sucked into the center of a plurality of plasma flames easily.

(2) The gas flow rate of a plurality of directions, preferably three-direction or more, combined plasma flames is not so fast, the speed of sucked starting material powder (e.g. metal powder) is slow and vaporized sufficiently.

(3) The whole amount of the starting material passes through the center portion of the high frequency

plasma.

(4) The whole amount of the starting material is vaporized.

(5) There is no adhesion of the starting material on the wall of high frequency plasma tube.

(6) The high frequency plasma is stable without making its flame disappear.

5 (7) It is possible to melt and vaporize a large amount of starting material powder.

As explained above, the hybrid plasma generating apparatus having the starting material supplying hole at the center of the top portion of the apparatus as shown in Fig. 1 has an ability of uniformly melt and vaporize the whole starting material supplied.

When a metal is used as the starting material in the hybrid plasma generating apparatus, it is preferable to use either one of an inert gas such as argon (Ar) or hydrogen gas or a mixture thereof.

10 The use of hydrogen gas gives the following advantages, that is, (i) oxygen and the like adhered to surfaces of starting material particles can be removed and the starting material can be activated, (ii) heat output of plasma can be raised, since hydrogen gas (H₂) is a two-atom molecule, and (iii) thus a high temperature can be obtained easily and a metal can be reduced, for example, by removing chlorine from a metal in the case of a metal chloride.

When metallic compounds or ceramics are used as the starting material, it is necessary to select starting materials considering the chemical reactions of the desired final product in the plasma flame or high-temperature gas currents or physical changes.

20 This invention is illustrated by way of the following Examples, in which all percents are by weight unless otherwise specified.

Example 1

The apparatus as shown in Fig. 2 was used. In Fig. 2, hybrid plasma is formed by combining three dc plasma currents 1 generated from dc plasma guns 3 and a high frequency plasma 2 generated by a work coil 4. A starting material supplying hole 5 is formed at the top of the apparatus and a starting material is supplied while excluding the air. There is a narrow portion (neck portion) 6 under the high frequency plasma generating portion. Under the narrow portion, a reactive gas inlet 7 is provided.

Using the above-mentioned apparatus, the operation was carried out under the following conditions.

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DC plasma output	15 KW x 3	(generally 10-30 KW x n)
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DC plasma gas (Ar)	15 l/min x 3	(generally 10-20 l/m x n)
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Sheath gas (Ar)	50 l/min
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High frequency plasma output	60 KW	(generally 50-200 KW)
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Inner diameter of hybrid 75 mm (± 20 mm)
reactor

Inner diameter of neck 50 mm (± 20 mm)
portion

Inner diameter of 80 mm (± 20 mm)
reactive gas inlet portion

Note) "n" means the number of dc plasma guns.

To this reactor, Si powder having a particle size of 100 μm to 44 μm and containing 1.43% of B uniformly was supplied from the supplying hole 5 at a rate of 4.2 g/min (generally 3-100 g/min being possible). The starting material powder dropped along the central axis of the dc plasma and the high frequency plasma and subjected to melting and vaporization. The temperature of the gas current at the front portion of the reactive gas inlet 7 was 1600 to 2000°C.

From the reactive gas inlet 7, a hydrocarbon gas such as CH_4 gas was supplied at a flow rate of 3.7 l/min (in principle about, stoichiometrical amount) to synthesize gray powder. The resulting powder was recovered by a bag filter provided in the later stage. The obtained powder had a particle size of 0.3 to 0.5 μm and a shape of sphere or cubic particles. The powder was β -SiC containing about 1% of B. Further, 0.5% of free carbon was contained in the resulting powder due to the addition of CH_4 gas slightly in excess with respect to the stoichiometric amount of Si charged. By controlling the amount of CH_4 gas, the amount of free carbon can be changed freely or free Si without free carbon can be produced.

In the apparatus shown in Fig. 2, the portion above the reactive gas inlet 7 is narrowed in order to prevent a back current toward the upper stream portion due to explosively rapid expansion of the charged reactive gas. When the back current takes place, a reaction between insufficiently grown particles or non-condensed gases takes place, which results in mixing with fine, uncontrolled shape of particles.

The produced powder collected by the bag filter was uniaxial pressed at 100 Kg/cm², followed by cold isostatic press (CIP) molding at 7000 Kg/cm². The green body had a density of 67% of theoretical density (TD). The green body was sintered at 2150°C in an Ar atmosphere for 30 minutes to give a SiC sinter body having a density of 99% or more of the theoretical density.

When β -SiC powder (particle size 0.3 μm) available commercially mixed with 1% of B_4C and 1% of C was CIP molded (green density: 62% of theoretical density) and sintered in the same manner as mentioned above. The resulting sintered body had a density of 97% of the theoretical density.

This shows that the product obtained by the process of this invention is superior to commercially available powder in molding properties and sintering properties.

Example 2

The process of Example 1 was repeated except for not introducing the reactive gas CH_4 . As a result, a brown spherical Si powder having a particle size of 0.3 to 0.5 μm was obtained.

Example 3

The process of Example 1 was repeated except that high purity Al powder was supplied at a rate of 3.0 g/min in place of the Si powder containing B, the temperature of gas stream before the reactive gas inlet was controlled at 1500 to 1900°C, and NH_3 or N_2 gas was introduced at a rate of 5 to 10 l/min to react with liquid sphere of Al. It is possible to feed NH_3 or N_2 several to ten times as much as the stoichiometrical amount. White AlN powder having a particle size of 0.1 to 0.3 μm was collected in a bag filter.

As mentioned above, according to this invention, there can be produced easily ceramic starting material powder, which is necessary for producing fine ceramic sintered bodies with high quality, having high purity, a particle size of 0.05 to 1.0 μm , a narrow particle size distribution, and a shape of sphere, cubic particles or similar shapes. Further, the difficulty in selecting starting materials is overcome by this invention.

Claims

1. A process for producing fine particles of a material in a plasma apparatus, which process comprises:
 - producing, using an anode surrounding a cathode, a direct current plasma current (1) on a central axis of a work coil (4) generating a high frequency induction plasma (2),
 - supplying the material as a starting material to the direct current plasma current (1) from a top portion (5) of the apparatus, and
 - passing the starting material through the centre portion of the high frequency plasma (2) to heat and vaporize the starting material, and
 - recovering particles resulting from the vaporization, **characterized in that**, ultrafine particles having an average particle size of 0.05 to 1.0 μm of a metal, a metallic compound or a ceramic, are produced while recovering the whole amount of the starting material, a plurality of direct current plasma currents (1), each produced using a respective anode surrounding a respective cathode, are combined on the central axis of the work coil (4) to produce a highly viscous direct current plasma flame, the direct current plasma (1) and the high frequency plasma (2) are connected to each other without separation between them, and the starting material is supplied, while excluding air, to the portion where the direct current plasma currents (1) combine and is sealed by the highly viscous direct current plasma flame and moved, as it is, along the central axis to the high frequency plasma (2).
2. A process as claimed in claim 1, which further comprises before the step of recovering resulting particles:
 - leading the vaporized material to a temperature region having a temperature equal or higher than the melting point and lower than the boiling point of the starting material to produce condensation growth of liquid spheres of the starting material,
 - contacting the liquid spheres with a reactive gas to effect a reaction therewith, and
 - collecting powder produced by the reaction.
3. A process as claimed in claim 2, wherein the reactive gas is a hydrocarbon or NH_3 or N_2 .
4. A hybrid plasma generating apparatus comprising means (3) constituted by an anode surrounding a cathode for generating a direct current plasma current (1) on the central axis of a work coil (4) for generating a high frequency induction plasma (2) and a hole (5) provided on the central axis at a top portion of the apparatus for supplying a starting material, **characterized in that**, for producing ultrafine particles having an average particle size of 0.05 to 1.0 μm of a metal, a metallic compound or a ceramic, while recovering the whole amount of the starting material, a plurality of means (3), each constituted by a respective anode surrounded by a respective cathode, for generating direct current plasma currents (1) are provided, said direct current plasma generating means (3) are placed so that, in use, the direct current plasma (1) and the high frequency plasma (2) are connected to each other without separation between them, and so that the direct current plasma currents (1) combine on the central axis of the work coil (4) to produce a highly viscous direct current plasma flame, and the said hole (5) is above the said direct current plasma generating means (3) and so placed that starting material is sealed, in use, by the highly viscous direct current plasma flame and moved along the central axis as it is to the high frequency plasma (2).
5. Apparatus as claimed in claim 4 for producing ultrafine particles of metals, metallic compounds and ceramics comprising a direct current plasma zone (1) produced, in use, by the means (3) for generating direct current plasma currents, and a high frequency plasma zone (2) produced, in use, by the work coil (4), wherein the plurality of means (3) for generating direct current are provided at the upper periphery portion of the direct current plasma zone (1), and a hermetic starting material supplying inlet (5) is provided at the centre of the top portion of said direct current plasma zone (1).
6. Apparatus as claimed in claim 5, which further includes a reaction zone including a reactive gas inlet (7) arranged under the high frequency plasma zone (2) via a narrow portion (6) between the high frequency plasma zone (2) and the reactive gas inlet (7).

Revendications

1. Un procédé de préparation de fines particules d'une matière dans un appareil à plasma, procédé qui

comprend :

la production, en utilisant une anode entourant une cathode, d'un courant de plasma en courant continu (1) sur un axe central d'un inducteur de chauffage (4) générant un plasma à induction haute fréquence (2),

la fourniture de la matière comme matière de départ au courant de plasma en courant continu (1) provenant d'une partie supérieure (5) de l'appareil, et

le passage de la matière de départ par la partie centrale du plasma haute fréquence (2) pour chauffer et vaporiser la matière de départ, et

la récupération de particules résultant de la vaporisation, **caractérisé en ce que**, des particules extrêmement fines ayant une taille moyenne de 0,05 à 1,0 μm d'un métal, d'un composé de métal ou de céramique, sont produites tout en récupérant la totalité de la matière de départ, une pluralité de courants de plasma en courant continu (1), chacun d'eux utilisant une anode respective entourant une cathode respective, sont combinés sur l'axe central de l'inducteur de chauffage (4) pour produire une flamme de plasma en courant continu hautement visqueuse, le plasma en courant continu (1) et le plasma haute fréquence (2) sont reliés l'un à l'autre sans séparation entre eux, et la matière de départ est fournie, tout en rejetant l'air, dans la partie où les courants de plasma en courant continu (1) se combinent et elle est enveloppée par la flamme de plasma en courant continu hautement visqueuse et est déplacée, en l'état, le long de l'axe central vers le plasma haute fréquence (2).

2. Un procédé selon la revendication 1, qui comprend en outre avant l'étape de récupération des particules résultantes :

le fait d'amener la matière vaporisée à une température égale ou supérieure au point de fusion et inférieure au point d'ébullition de la matière de départ pour produire une augmentation de la condensation des sphères liquides de la matière de départ,

la mise en contact des sphères liquides avec un gaz réactif pour provoquer une réaction avec celui-ci, et

la collecte de la poudre produite par la réaction.

3. Un procédé selon la revendication 2, où le gaz réactif est un hydrocarbure ou NH_3 ou N_2 .

4. Un dispositif générant du plasma hybride comprenant des moyens (3) constitués d'une anode entourant une cathode pour générer un courant de plasma en courant continu (1) sur l'axe central d'un inducteur de chauffage (4) pour générer un plasma à induction haute fréquence (2) et un orifice (5) prévu sur l'axe central en haut du dispositif pour fournir une matière de départ, **caractérisé en ce que**, pour produire des particules extrêmement fines ayant une taille moyenne de 0,05 à 1,0 μm d'un métal, d'un composé de métal ou de céramique, tout en récupérant la totalité de la matière de départ, une pluralité de moyens (3), constitués chacun d'une anode respective entourée par une cathode respective, pour générer des courants de plasma en courant continu (1) sont prévus, lesdits moyens de génération de plasma en courant continu (3) sont situés de sorte que, en utilisation, le plasma en courant continu (1) et le plasma haute fréquence (2) sont reliés l'un à l'autre sans séparation entre eux, et de sorte que les courants de plasma en courant continu (1) se combinent sur l'axe central de l'inducteur de chauffage (4) pour produire une flamme de plasma en courant continu hautement visqueuse, et ledit orifice (5) est au-dessus desdits moyens de génération du plasma en courant continu (3) et est situé de façon à envelopper la matière de départ, en utilisation, par la flamme de plasma en courant continu hautement visqueuse et à la déplacer en l'état le long de l'axe central vers le plasma haute fréquence (2).

5. Un dispositif selon la revendication 4 pour produire des particules extrêmement fines de métal, de composé de métal et de céramique comprenant une zone de plasma en courant continu (1) produite, en utilisation, par les moyens (3) pour générer des courants de plasma en courant continu, et une zone de plasma haute fréquence (2) produite, en utilisation, par l'inducteur de chauffage (4), où une pluralité de moyens (3) pour générer le courant continu sont prévus dans la partie périphérique supérieure de la zone de plasma en courant continu (1), et une arrivée de matière de départ hermétique (5) est prévue au centre de la partie supérieure de ladite zone de plasma en courant continu (1).

6. Dispositif selon la revendication 5, qui comprend en outre une zone de réaction comprenant une arrivée de gaz réactif (7) située sous la zone de plasma haute fréquence (2) via une partie étroite (6) entre la zone de plasma haute fréquence (2) et l'arrivée de gaz réactif (7).

Patentansprüche

1. Verfahren zum Herstellen feiner Partikel eines Materials in einer Plasmavorrichtung, das folgende Verfahrensschritte aufweist:
 5 Erzeugen unter Verwendung einer eine Kathode umgebenden Anode eines Gleichstromplasmastroms (1) auf einer Zentralachse einer Arbeitswicklung (4), die ein Hochfrequenzinduktionsplasma (2) generiert,
 Zuführen des Materials als Ausgangsmaterial an den Gleichstromplasmastrom (1) von einem oberen Abschnitt (5) der Vorrichtung, und
 10 Befördern des Ausgangsmaterials durch den Zentralabschnitt des Hochfrequenzplasmas (2), um das Ausgangsmaterial zu erhitzen und zu verdampfen, und
 Wiedergewinnen der durch das Verdampfen entstehenden Partikel, **dadurch gekennzeichnet**, daß ultrafeine Partikel mit einer durchschnittlichen Partikelgröße von 0,05 bis 1,0 μm eines Metalls, einer Metallverbindung oder eines Keramikmaterials hergestellt werden, wobei die gesamte Menge des
 15 Ausgangsmaterials wiedergewonnen wird, mehrere Gleichstromplasmaströme (1), die jeweils unter Verwendung einer zugehörigen Anode, die eine zugehörige Kathode umgibt, erzeugt werden, auf der Zentralachse der Arbeitswicklung (4) kombiniert werden, um eine hochviskose Gleichstromplasmaflamme zu erzeugen, wobei das Gleichstromplasma (1) und das Hochfrequenzplasma (2) miteinander ohne zwischenliegende Trennung verbunden sind, und wobei das Ausgangsmaterial unter Ausschluß von Luft
 20 an den Abschnitt geliefert wird, wo sich die Gleichstromplasmaströme (1) vereinigen, und das Ausgangsmaterial durch die hochviskose Gleichstromplasmaflamme eingeschlossen und, wie es ist, entlang der Zentralachse zu dem Hochfrequenzplasma (2) bewegt wird.
2. Verfahren nach Anspruch 1, das ferner vor dem Verfahrensschritt des Wiedergewinnens resultierender
 25 Partikel aufweist:
 Führen des verdampften Materials zu einem Temperaturbereich mit einer Temperatur gleich oder höher als der Schmelzpunkt und geringer als der Verdampfungspunkt des Ausgangsmaterials, um eine Kondensationsentwicklung von flüssigen Tröpfchen des Ausgangsmaterials zu erzeugen,
 Inkontaktbringen der flüssigen Tröpfchen mit einem reaktiven Gas, um eine Reaktion damit zu
 30 bewirken, und
 Sammeln eines durch die Reaktion entstandenen Pulvers.
3. Verfahren nach Anspruch 2, wobei das reaktive Gas Kohlenwasserstoff oder NH_3 oder N_2 ist.
- 35 4. Hybridplasma-Generierungsvorrichtung mit: einer Einrichtung (3), die durch eine eine Kathode umgebende Anode gebildet wird, zum Generieren eines Gleichstromplasmastroms (1) auf der Zentralachse einer Arbeitswicklung (4) zum Generieren eines Hochfrequenzinduktionsplasmas (2) und einer Öffnung (5), die auf der Zentralachse an einem oberen Abschnitt der Vorrichtung zum Zuführen eines
 40 Ausgangsmaterials vorgesehen ist, **dadurch gekennzeichnet**, daß zum Herstellen ultrafeiner Partikel mit einer durchschnittlichen Partikelgröße von 0,05 bis 1,0 μm eines Metalls, einer Metallverbindung oder eines Keramikmaterials, wobei die gesamte Menge des Ausgangsmaterials wiedergewonnen wird, mehrere Einrichtungen (3) zum Generieren von Gleichstromplasmaströmen (1) vorgesehen sind, die jeweils durch eine zugehörige eine zugehörige Kathode umgebende Anode gebildet werden, wobei die Gleichstromplasmagenerierungseinrichtungen (3) so angeordnet sind, daß im Betrieb das Gleichstrom-
 45 plasma (1) und das Hochfrequenzplasma (2) miteinander ohne eine zwischenliegende Trennung verbunden sind und so, daß die Gleichstromplasmaströme (1) sich auf der Zentralachse der Arbeitswicklung (4) vereinigen, um eine hochviskose Gleichstromplasmaflamme zu bilden, und sich die Öffnung (5) oberhalb der Gleichstromplasmagenerierungseinrichtungen (3) befindet und so angeordnet ist, daß das Ausgangsmaterial im Betrieb durch die hochviskose Gleichstromplasmaflamme eingeschlossen und, wie es ist, zu dem Hochfrequenzplasma (2) entlang der Zentralachse bewegt wird.
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5. Vorrichtung nach Anspruch 4, zum Herstellen ultrafeiner Partikel von Metallen, Metallverbindungen und Keramikmaterialien, mit: einer Gleichstromplasmazone (1), die im Betrieb durch die Einrichtungen (3) zum Generieren von Gleichstromplasmaströmen erzeugt wird, und einer Hochfrequenzplasmazone (2),
 55 die im Betrieb durch die Arbeitswicklung (4) erzeugt wird, wobei die mehreren Einrichtungen (3) zum Generieren des Gleichstroms an dem oberen Umfangsabschnitt der Gleichstromplasmazone (1) vorgesehen sind und ein hermetischer Ausgangsmaterial-Zuführeinlaß (5) am Zentrum des oberen Abschnitts der Gleichstromplasmazone (1) vorgesehen ist.

6. Vorrichtung nach Anspruch 5, die ferner eine Reaktionszone mit einem Reaktivgaseinlaß (7) aufweist, der unterhalb der Hochfrequenzplasmazone (2) über eine Verengung (6) zwischen der Hochfrequenzplasmazone (2) und dem Reaktivgaseinlaß (7) angeordnet ist.

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FIG. 1

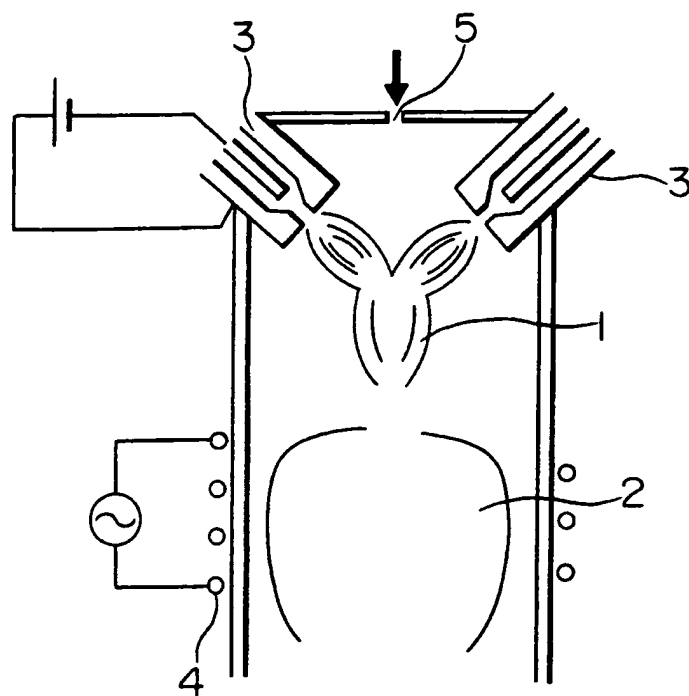


FIG. 2

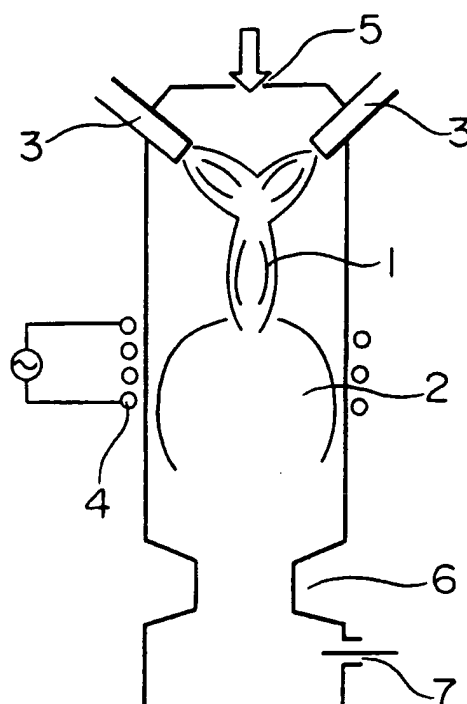


FIG. 3

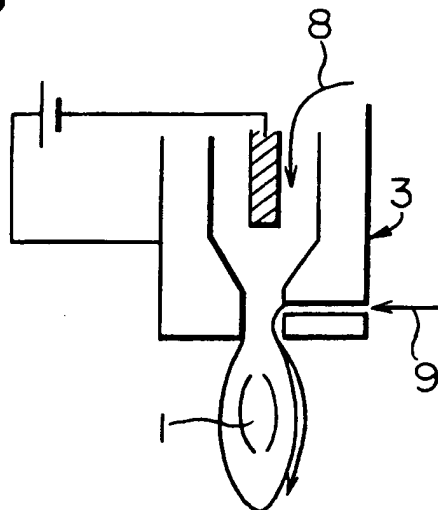


FIG. 4

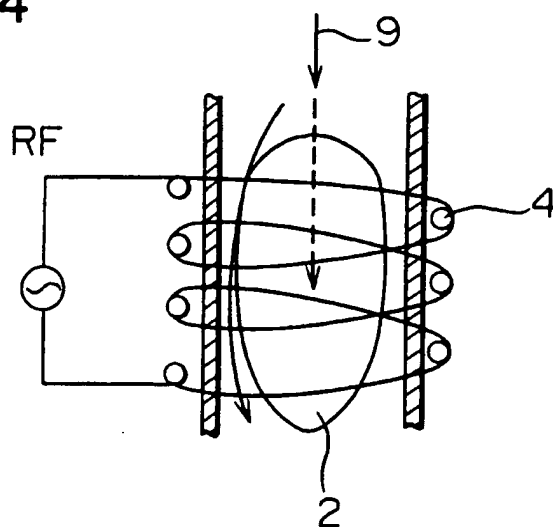


FIG. 5

